Application of Resilience concept for enhanced management of water supply systems

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Abstract

This paper presents an approach to developing indicators for expressing resilience of a generic water supply system. The system is contextualised as a meta-system consisting of three subsystems to represent the water catchment and reservoir, treatment plant and the distribution system supplying the end-users. The level of final service delivery to end-users is considered as a surrogate measure of systemic resilience. A set of modelled relationships are used to explore relationships between system components when placed under simulated stress. Conceptual system behaviour of specific types of simulated pressure is created for illustration of parameters for indicator development. The approach is based on the hypothesis that an in-depth knowledge of resilience would enable development of decision support system capability which in turn will contribute towards enhanced management of a water supply system. In contrast to conventional water supply system management approaches, a resilience approach facilitates improvement in system efficiency by emphasising awareness of points-of-intervention where system managers can adjust operational control measures across the meta-system (and within subsystems) rather than expansion of the system in entirety in the form of new infrastructure development.

Keywords – resilience, critical capacity, climate change, water supply, service delivery.

1. Introduction

The provision of potable water is considered as an essential service in most countries. Water supply systems have been developed at different scales for this purpose. The main objective of a water supply system is the reliable and safe supply of potable water to consumers. Very large-scale and complex water supply systems that operate at a regional level, such as the South East Queensland Water Supply System (SEQ Water Grid) are the result of an approach to improve the reliability of potable urban water supply and implemented at very significant cost. However, significant challenges must be overcome in managing the provision of potable water. As water is a natural resource, the dependency on natural phenomena such as climatic conditions and hydrology is very high and poses a unique set of challenges. Climate change and increasing demand due to population growth are two significant factors or pressures that add to these challenges.

A water supply system has certain unique characteristics that differentiate it from other infrastructure systems. Many systems, such as transport, power or telecommunication networks are technical systems, operating within specified and relatively easily identifiable boundaries. In contrast, a water supply system is a combination of diverse subsystems. A generic water supply system consists of a supply catchment and a reservoir, treatment plant and the distribution system, which range from socio-ecological to technical domains. Due to this complexity and the diverse nature of the component parts of a water supply system, different management approaches need to be applied to ensure efficient and reliable supply. Resilience as a management concept is explored here for application in the water supply arena to overcome the challenges faced.

Considering the various challenges in the area of water supply management, a critical issue is the lack of understanding of system behaviour under changing climate conditions. Due to high dependency of water inflow to the system being influenced by climate conditions, an in-depth knowledge of system response to climate change will help to guide decision makers in being proactive in the development of robust management strategies. The concept of resilience acknowledges provisions for dealing with adverse conditions or 'pressure' being applied on the system. 'Pressure' is defined here as any force that pushes the system towards a low level of service delivery. However, the development of suitable approaches to operationalise the concept of resilience and thereby apply it to a water supply system is not a simple exercise.

This paper outlines an approach to assessing a suite of indicators to better understand how the concept of resilience can be applied to a water supply system. The approach taken here is to explore a water supply system in entirety by initially identifying dependencies and interconnectedness of processes and then disaggregating these relationships to define parameters that express system behaviour. These parameters can be developed as indicators which demonstrate resilience characteristics of the system, as resilience cannot be measured directly. The knowledge of resilience characteristics such as pressure absorption capacity will help to develop a decision support capacity for enhanced management of a water supply system.

South East Queensland (Australia) Water supply system (SEQ Water Grid) is the case study area where the investigations were undertaken. This system is a complex regional water supply system with a high degree of connectivity between supply sources and treatment plants. South East Queensland is a region with high population growth rate (ABS 2012) and generally dry (BOM 2012), but significantly vulnerable to climate change impacts.

2. Resilience

2.1 Definitions

Many interpretations of resilience can be found in research literature (Gunderson. 2000, Holling 1973, Brock et al 2002, Walker et al 2002, Adger 2000, IPCC 2007). The fundamental premise of these definitions is similar, but addresses different aspects of the concept. For example, Holling (1973) considered the term to refer to a 'measure of the persistence of the system' while Gunderson (2000) preferred an 'amount of disturbance that the system can absorb'. Due to the broad nature of the concept, it is applicable to many disciplines. For example, Madani and Jackson (2009) have noted that resilience as a concept is applicable for examining ecological systems, economies and business entities, industrial and organisational bodies, networks, psychological behaviours, and socio-ecological systems to understand the dynamics and to make use of that knowledge for developing decision support applications. Also there are other examples of resilience-focused research in areas of "Resilient cities" (Pickett et. al 2003) and "Resilient Societies" (Allenby and Fink 2005).

The diverse interpretations of the term 'resilience', is one of the major issues confronting researchers and end-users alike in resilience related studies. For the purposes of this study, 'resilience' is conceived as the 'ability to withstand' or 'recover functionality quickly' after being placed under pressure or a degree of disturbance.

Three important aspects of resilience highlighted by Wang and Blackmore (2009) are of significance to this work. The first of these is a system's ability to limit crossing a performance threshold – into degraded performance. Generally, systems operate within a defined range of parameters. When operating under extreme or abnormal conditions, the system tends to move towards and beyond minimum acceptable or threshold performance levels. The more resilient the system, the more effective is the ability to maintain the performance level above the threshold. This characteristic also emphasises the capacity of the system to absorb 'pressure' while sustaining function. The second and third characteristics identified by Wang and Blackmore (2009) are the ability to recover after failure-causing events and the adaptive capacity that characterises an inherent capability to adjust functionality of system properties and thus adapt.

A complex and important issue in resilience related studies is how to measure resilience itself. Haimes (2009) has pointing out that the resilience of a system cannot be characterised with a single numerical descriptor. Attempts to compare the resilience of different systems could result in misleading outcomes unless these different systems are analysed on the basis of being subjected to the same levels of threats along with the same specific probabilities. In view of this, the resilience of a system could be measured in terms of a myriad of sub-states that can characterise the system for a specific time period and threats that it will be subjected. Haimes (2009) has further pointed out that, measuring the efficacy of a system's resilience might be achieved through the unique functionality of that particular system and its responses (outputs) to specific inputs. This study is focused on contributing a way forward on the issue of assessing resilience of a generic water supply system by means of evaluating suitable indicators.

2.2 Concepts of resilience applicable to a water supply system.

Application of resilience thinking as a management concept in the field of water supply needs careful evaluation. Although a water supply 'system' can appear to be a single system, the complete system consists of different subsystems. Thus, the entire system can be considered as a meta-system which is comprised of interconnected subsystems (see Figure 1).

A water supply system as a meta-system is examined later in this paper. Water catchment and the reservoir is part of a bio-ecological subsystem. Consequently it is vulnerable to climate variability pressures. Treatment plant and distribution infrastructure and the users belong to socio-ecological and technical environments. Hence, the base concepts applicable to a water supply system range from technical to socio-ecological contexts. Barnes et.al (2012) highlighted the resilience properties of these different system concepts as given in the Table 1.

Table 1: Resilience: From technical to a broader Social –Ecological contexts

System concept	***Characteristics***	***Focus***	***Context***
Technical	*Return time efficiency*	*Recovery, Constancy*	*Vicinity of a stable equilibrium*
Ecological	*Buffer capacity, withstand shock, maintain function*	*Persistence, Robustness*	*Multiple equilibrium, stability landscape*
Socio- ecological	*Interplay disturbance & reorganization, sustaining & development*	*Adaptive capacity, transformability, learning innovation*	*Integrated system feedback, dynamic interactions.*

Comparing technical and socio-ecological system concepts, it has been found that technical systems generally have specified operational conditions holding low 'pressure' absorption characteristics. Hence 'return time to efficiency' is a more appropriate characteristic that designates a contributor to resilience of a technical system. Temporal factors are different in socio-ecological systems. The transition from one functional state to another may not be sudden. More flexibility and redundancy could be seen within the system. Therefore, in socio-ecological systems, the ability to withstand shock and buffer capacity to characterise the resilience of such systems is available. A complete water supply system being in socio-ecological and technical domains, the applicable base concepts range from technical to socio-ecological contexts.

Acknowledgement of resilience characteristics of technical, ecological or socio-ecological contexts is a key step forward in the process of developing appropriate indicators to assess resilience of the system. These characteristics provide the platform for identifying the parameters that recognise system behaviour which are essential for indicator development.

2.3 Resilience as a management concept.

Achieving management goals within such complex systems are non-routine, especially in the face of climatic change. Depending on climatic conditions and availability of resources, one approach to satisfy demand beyond full system capacity level, is to expand the system by building new infrastructure. That is a part of a supply side improvement and management process.

A completely different approach is to understand the system components, especially their characteristics and capabilities in order to manage the relationships between these and make use of that knowledge to manipulate management strategies to achieve maximum efficiencies, thus obviating the need to resort to the commonly adopted option of new infrastructure creation. This approach presumes that effective decision support systems can be utilised to select appropriate demand management options. For the development of a reliable decision support system, in-depth understanding of system behaviour under difficult conditions that are likely to push system functionality beyond the threshold limit is a key pre-requisite. Knowledge of resilience allows decision makers timely reactions at trigger points to enable the formulation of the most appropriate management strategy. Identification of the trigger points under uncertain conditions is a key to enhancing efficient management practices. Knowledge of resilience of the system signals decision makers about the correct time frame for new infrastructure development by acknowledging critical boundaries beyond which the system will be unable to function properly.

3. Indicators to characterise resilience through system behaviour.

Resilience not being a directly measurable property, characterising resilience by means of suitable indicators is the approach adopted in the study. Accordingly, the first step is to identify 'surrogate resilience measure/s' (measure from which the level of resilience of the system is interpreted) and identify parameters that provide more details of the surrogate measure. These parameters can then be employed to deliver a set of indicators that gives further information or values by which variations of that surrogate measure is recognised, and in turn the information to characterise the resilience of the system by understanding the ability of the system to withstand a pressure or ability to recover after a failure event.

According to NHS (2012), *"Indicators are succinct measures that aim to describe as much about a system as possible in as few points as possible. Indicators help us understand, compare it and improve it.* The indicators in this study should provide information to assess the resilience capabilities of the system. The process of identifying the relevant parameters is discussed after a detailed discussion of a generic water supply system and its behaviour.

Dimic (2010) highlighted essential criteria that good indicators should have as proposed by the National Quality Forum (http://www.qualityforum.org). These are; importance, scientific acceptability, feasibility and usability.

- *Importance:* The indicator must be relevant to similar systems and must relate specifically to the objective in the question.
- *Scientific acceptability:* The measure must be reliable and valid. Reliable means the indicator must give the same results in repeated measures and valid means it must measure what is intended to measure.
- *Feasibility*: Data for the indicator must be feasible to be obtained.
- *Usability:* The results of any measures must be understood by the intended audience. Measures that are difficult to understand will not be translated to meaningful improvement.

In the process of developing indicators, it is important to ensure that the proposed indicators satisfy the above criteria. However, notable limitations also exist in the use of indicators. A unique criterion may not be suitable for decision making for all systems. Depending on the nature of the system (geographical area, maximum capacity, type of source), different indicators or different decision criteria may need to be used for decision making.

4. Water supply system as a meta-system.

The first step in the operationalisation of systemic resilience is defining a high-order description of the system. The approach taken here is to define a complete water supply system and consider application of the resilience concept across three significant and different domains: water catchment and the reservoir; treatment plant; and the distribution to end users. Integration of the three components form a complete water supply system or meta-system as depicted in Figure 1. The 'foot print' of one component (or subsystem) on the other illustrates the degree of interconnectedness between subsystems.

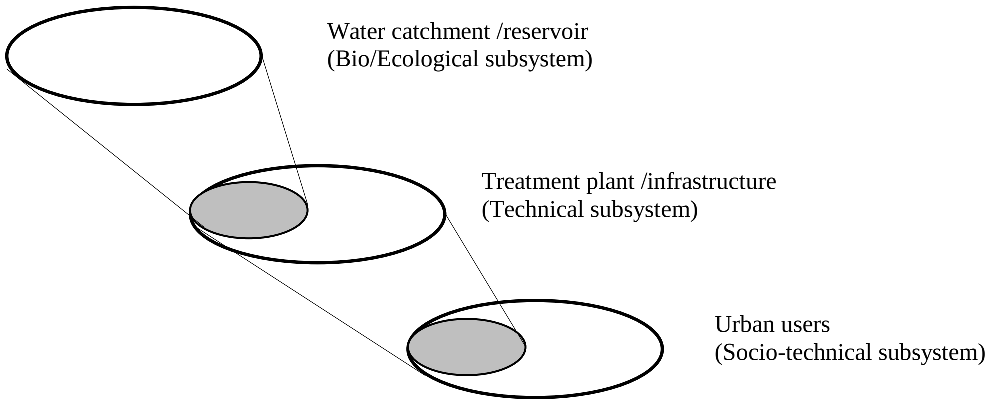

Figure 1: Interdependent domains as a meta-system (adapted from Barnes et al. (2011)

The diverse nature of multiple subsystems, ranging from socio-ecological to technical, adds a high level of complexity to the meta-system. In a resilience focused study, determination of the final output is important for relating the system's service delivery ability to an adverse force which may tend to reduce this ability. Each subsystem has a maximum capacity for the appropriate operation of that subsystem. For example, the reservoir has a maximum storage capacity and the treatment plant has a maximum treatment capacity. The lowest maximum capacity determines the final output as that will limit the potential of the system.

The maximum capacity of the subsystem that limits the final output is defined here as the ‘critical capacity.’ Although other subsystems may have excess capacity, the final output will be governed by this critical capacity. Subject to the critical capacity limitation, the meta-system would exhibit a maximum level of output (service). The level of output at any given time (qualitatively and quantitatively) available for end users compared to the maximum service level is a surrogate resilience measure of the system. A surrogate measure is required here as a means of understanding level of resilience since resilience cannot be measured directly. The system’s ability to operate under unfavourable conditions is represented by the level of service delivery.

However, it is a misconception to consider uninterrupted service provision as a manifestation of high resilience of the system. A reason for such continuity could be due to the absence of pressure being applied on the system. Under a non-pressure situation, even a non-resilient system (which has no resilient characteristics) may provide uninterrupted service. A system is resilient if uninterrupted service is provided under pressure or if able to recover without causing a significant impact when put under pressure.

On the other hand, even a resilient system will not be able to supply services exceeding a certain capacity as there is a limit to which any aggregated capacity will be exceeded. For example, demand by a population above the ‘system population’ cannot be expected to be satisfied fully. System population is defined as the maximum population that the system is capable of supplying subject to the ‘critical capacity’. In this situation, failure to satisfy excessive demand is due to exceeding of capacity and not due to low resilience of the system.

4.1 Selected stresses on the system

The first and the most important process is water storage at the first level of the system. All the other processes depend on the success of water storage. Water inflow to the storage reservoir is highly dependent on climatic conditions. The climatic conditions are not very accurately predictable. Adverse climatic conditions leading to a reduction in water inflow will exert pressure on the subsequent processes of a water supply system resulting in the reduction of final service delivery by the system. Apart from the reduction of inflow, climate change can also contribute to the degradation of water quality (Delpla et al, 2009, Park et al. 2010, Ducharme 2008). For example, increased temperature associated with high nutrient loads can lead to eutrophication and algae growth in the reservoir. Therefore, climate change is a major pressure generator on a water supply system which is dependent of surface water for storage.

Increase in population will also create stress on the system due to the compounding increase in water demand. A concomitant consequence of population increase is rapid urbanisation which will also contribute to degrading water quality due to the creation of new pollutant sources and increase in pollutant loads (Goonetilleke and Thomas 2003). Hence, climate change and population growth are two major influential factors which exerts pressure on a water supply system. The response of the system to these pressures will indicate the level of resilience and the response is considered as the level of output (service).

4.2 Relationship of resilience and system behaviour

Having identified the surrogate measure of resilience as the final level of service delivery, the next challenge is to identify the relationship between resilience and the changes in system behaviour due to pressure. Evaluation of interdependencies of parameters reveals the relationships. A disturbance acts as a pressure applied on the system. Pressure creates 'stresses' on the system. Stresses are the conditions that compel the system to define (or reduce) the final service level. The stresses on the system are '*low water availability in the reservoir*' and '*low quality of available water*'. Level of final service delivery depends on the amount of stresses on the system. A resilient system delivers a relatively higher level of services even under a highly stressful situation. As the level of service delivery is a surrogate measure of resilience, a first degree relationship of resilience-service delivery can be expressed as follows;

$$Rs = f\,(S_d, a) \text{.....................................} \quad \text{(Equation 1)}$$

Where Rs - Resilience of the system
S_d - Service delivery
a - other variables that influence resilience of the system

Notes:

- In deriving this equation, the entire the meta-system has been taken into consideration.
- Service delivery is the final output that the system delivers to the end users.
- Level of service delivery is measured with respect to the maximum supply capacity of the system.

Disaggregating further down to the second degree level, service delivery and stresses can be related as:

$$S_d = f\,(S_r, b) \text{.................................} \quad \text{(Equation 2)}$$

Where S_r - Stresses on the system
b- other variables that influence service delivery

Considering the variables that contribute to stresses on the system, a third degree relationship can be developed as given below. Inadequate inflow or higher demand can result in *low water availability*. Low quality of inflow water and degradation of reservoir water contribute to *low quality of available water*. The third degree relationship, similar to the one introduced by Barnes et al. (2012), can be defined as:

$$Sr = f\,(\sum I_f, Q_{in}, Q_s, D_m, c) \text{.............} \quad \text{(Equation 3)}$$

Where I_f - Inflow to the reservoir
Q_{in} - Quality of inflow water
Q_s - Quality of water in the reservoir
D_m - Demand

c - Other variables

These expressions indicate the variables that contribute to cause stress on the system. Disaggregating further down to the next level of relationships will help to relate these variables to the forces that influence changes to the variables. This service delivery- stress- pressure relationship is an important link to understand system behaviour under pressure which indicates the level of resilience of the system.

4.3 System behaviour under pressure

Analysis of system behaviour under pressure acknowledges that parameters can indicate sensitivity of the modelled system and thus define possible tipping points or transitional limits within the system. Two critical pressure limits that affect system functionality can be identified. They are the 'design limit' and the 'threshold limit' of pressure. The design limit is the pressure for which the system is designed. The system is expected to function without interruption of supply until the applied pressure reaches the design pressure limit in a situation where pressure gradually increases. However, the system (if resilient) might function and provide services even beyond this pressure limit. The threshold limit is the pressure limit at which point the system is unable to provide minimum acceptable level of service. To visualise system behaviour under pressure, a hypothetical system behaviour corresponding to an increasing pressure event is illustrated in Figure 2. It is assumed that the system recovers partially. Below the design pressure limit, the system functions without interruption and when the pressure limit exceeds the design limit, service reduction takes place.

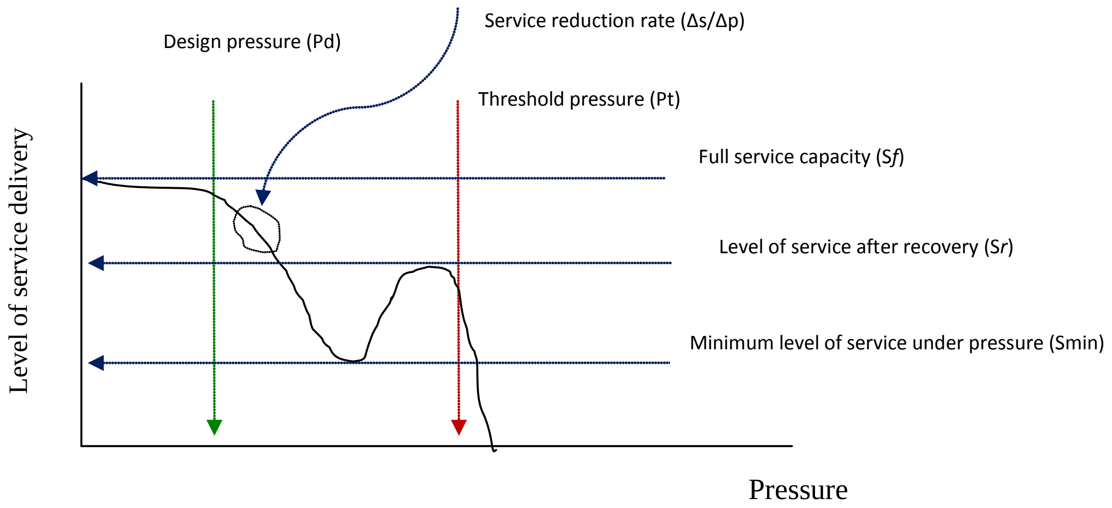

Figure 2: System behaviour represented by level of service delivery under pressure

A suite of essential parameters (such as design and threshold pressure limits, rate of service reduction, full service capacity level, service level after recovery, minimum level of service under pressure) that indicate behaviour changes can be identified by a careful evaluation of system behaviour as illustrated in Figure 2. The system behaviour is expressed in terms of level of service delivery. As service delivery is related to resilience as per equation 1, the level of resilience of the system can be expressed by these parameters.

These parameters may give a set of individual values which may not provide a sense of behaviour changes. However, these parameters can be arranged to give one or a family of indicators to quantify the behaviour changing characteristics. An attempt to generate a set of indicators to interpret resilience is a significant step forward in the adoption of the resilience concept in water supply system management. As part of our ongoing research we hope to develop a set of indicators which can be used as a tool to assess resilience of a water supply system to potential pressures.

5. Conclusions

Application of the resilience concept for enhanced management of a water supply system has been introduced here. The paper provides an innovative approach for evaluating the behaviour of a water supply system (considering as a nested system) under pressure and introducing a pathway to identify parameters that recognise the behaviour variations. While the work defines the initial steps, the fully developed modelling approach will contribute to enhancing the management of water supply systems in a resilient context based on the embedded ability to absorb or respond to disturbance.

To-date only limited approaches have been made to operationalise the application of resilience concept for the management of a water supply system. Consequently, a robust methodology has not been developed for assessing the resilience of a water supply system. Development of a robust methodology is challenging due to the diverse nature of the types of pressure that can act on a water supply system. A resilience approach is an imrovement from the conventional management strategies. Therefore, the proposed pathway for developing a suite of indicators can contribute to the enhanced management of water supply systems which are subjected pressure such as climate change and population growth impacts.

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